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Environmental research joint ventures and time-consistent emission tax: Endogenous choice of R&D formation☆

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ABSTRACT

This paper provides a new analytical framework of endogenous choice for environmental R&D formation. Furthermore, this paper presents an examination of environmental R&D of four types in a Cournot duopoly in a setting where a regulator has no precommitment ability for an emission tax. Results reveal that if the environmental damage is slight, or given severe environmental damage and large inefficiency in environmental R&D costs, then social welfare under environmental research joint venture (ERJV) cartelization is higher than in the other three scenarios: environmental R&D competition, environmental R&D cartelization, and ERJV competition. However, if environmental damage is severe, and if a firm's R&D costs are limited, then, in stark contrast to results of previous studies, environmental R&D competition is socially superior to any of the other three scenarios, although R&D competition is a case without information sharing and R&D coordination.

1. Introduction

Innovation is strongly encouraged by both competition and cooperation among firms with market power. It should be regarded as a part of the design of a competition policy. The truth is that research joint ventures (RJVs) used to be taboo in US competition policy until the US government enacted the National Cooperative Research Act (NCRA) in 1984.[1] In 1961 the Japanese government enacted the Act on Mining and Manufacturing Industry Technology Research Association on the model of the research association system in the UK (see Nakamura et al. (1997) and Sakakibara and Cho (2002)). This law increased the number of RJVs formed in Japan. At that time, Japanese firms had poor access to resources compared to companies in other economically developed countries. For that reason, the Japanese government recommended that firms form RJVs. As a consequence, the shortage of funds of many Japanese companies induced a strategic move to RJV. Forming a RJV is now regarded as a firm's usual strategy to survive market competition.[2] In the competition policies of many developed countries, RJVs are allowable subject to a *rule of reason* rather than being illegal *per se*.[3]

In Japan, 20 major firms involved in petroleum and chemical industries established the "Research Association of Refinery Integration for Group-Operation (RING)" in May 2000.[4] The main purpose of RING is to encourage RJV projects for cost-effective plant operation and emissions' reduction among participants to enhance a competitive advantage and to survive in the international market. Particularly with respect to RING's ERJV projects, the striking characteristic is that research

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[1] Caloghirou et al. (2003); Caloghirou et al. (2004) and Motta (2004) described historical, legal, and economic explanations for RJV. Grossman and Shapiro (1986) provided important arguments related to RJV and antitrust guidelines. These studies are useful for understanding the antitrust policies of influential countries and regions.

[2] For details of RJV studies, see Katsoutacos and Ulph (1998); Amir (2000a); Cassiman (2000); Vilasuso and Frascatore (2000); Caloghirou et al. (2003); Leahy and Neary (2005); Atallah (2007) and Shibata (2014).

[3] The *rule of reason* is a legal doctrine of antitrust law (the Sherman Act). Christiansen and Kerber (2006, p.217) presented the classic definition of the *rule of reason*: "The court must ordinarily consider the facts peculiar to the business to which the restraint is applied; its condition before and after the restraint was imposed; the character of the restraint and its effect, actual or probable. The history of the restraint, the evil believed to exist, the reason for adopting the particular remedy, the purpose or end sought to be attained, are all relevant facts" (Chicago Board of Trade v. United States, 246 U.S. 231 (1918)). The essence of the *rule of reason* is that, in the context of competition policy, it is indispensable to evaluate positive effects as well as negative effects produced by firms' coordination behavior. The economic evaluation presented in this paper is consistent with this doctrine. For details of the *rule of reason*, see Areeda (1986) and Christiansen and Kerber (2006).

[4] For details, see RING's website (http://www.ring.or.jp/).

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Table 1
Four scenarios.

Scenarios	R&D stage	Production stage (after R&D stage)
Environmental R&D competition (case N)	Firms compete. Each firm decides its own environmental R&D investment level to maximize its own profit given R&D investments of the rival.	Firms compete (under emission tax policy). Emissions are reduced by the firm's environmental R&D investment and some spillover effects from rivals' results of R&D activity.
Environmental R&D cartelization (case C)	Each firm coordinates its own environmental R&D investment level to maximize joint profits.	Firms compete (under emission tax policy). Emissions are reduced by the firm's environmental R&D investment and some spillover effects from rivals' results of R&D activity.
ERJV competition (case NJ)	Firms agree to form an ERJV to avoid duplication of R&D activities. Firms fully share the resulting technologies of environmental R&D. The degree of technological spillover is perfect. However, each firm chooses its own R&D investment level non-cooperatively to maximize its own profit.	Firms compete (under emission tax policy). Emissions are reduced by the sum of all environmental R&D efforts in the industry.
ERJV cartelization (case CJ)	Firms agree to form an ERJV to avoid R&D activity duplication. Firms fully share the resulting environmental R&D technologies. The degree of technological spillover is perfect. Firms coordinate their R&D investment levels to maximize joint profits.	Firms compete (under emission tax policy). Emissions are reduced by the sum of all environmental R&D efforts in the industry.

consortia consist of firms belonging to different industries. Apparently, the participating firms have intentionally avoided a horizontal ERJV to avoid exposure to prosecution for violation of antitrust laws. Is a horizontal ERJV socially harmful, or beneficial? At least the Japanese antitrust authorities have not earnestly considered the question. Other countries might have similar organizations.

In the field of economics of environmental regulation, several studies have been undertaken to reveal better R&D formation to internalize environmental externalities with a highly advanced emission abatement technology or to improve environmental quality (e.g., Chiou and Hu (2001); Poyago-Theotoky (2007, 2010); Yakita and Yamauchi (2011); Kesavayuth and Zikos (2012); Nimubona and Benchekroun (2015), and Ouchida and Goto (2016)).[5] However, clear-cut and comprehensive policy maps of socially efficient R&D formations corresponding to various regulatory circumstances are not still provided. With respect to forming an RJV, Grossman and Shapiro (1986, Section 4) point out that two conflicting effects exists: social benefits and anticompetitive dangers. Furthermore, in the field of law and policy, it has been considered that RJV should be evaluated from the perspective of a *rule of reason*. Nevertheless, investigations and discussions of RJV for emissions' reduction are utterly inadequate. Unfortunately, evaluation under a *rule of reason* lags far behind real-world environmental innovation. Therefore, the question persists: under what circumstances is RJV in an environmental area socially justified? This question has not been answered. This paper presents an examination of the question of whether environmental research joint venture (ERJV) formation within a symmetric R&D/Cournot model improves social welfare.

To investigate that question analytically, following the well-known definition of R&D scenarios by Kamien et al. (1992, p.1295), we introduce two ERJV formation scenarios into a setting where a regulator has no precommitment ability for an emission tax (i.e., time-consistent emission tax) [see Table 1[6]]: ERJV competition and ERJV cartelization. In the cases of such ERJV formation, both firms must agree to share environmental R&D findings completely before the R&D stage. The difference between ERJV competition and ERJV cartelization lies in the absence or presence of coordination of each firm's R&D effort level in the R&D stage.

From the viewpoint of profit-maximization, firms choose the most privately preferable environmental R&D formation among allowable R&D formations. However, that plan is not always realized because the actual R&D formation is the product of strategic interactions between firms facing government regulations. Then, what is the mechanism of a firm's endogenous choice of environmental R&D formation? No studies have explored this question. For that reason, this paper presents development of a new analytical framework. To describe a firm's endogenous choice of environmental R&D formation including ERJV formations more precisely, it is necessary to consider the following two points. One is game timing. The other is the assumption of controllability of R&D spillover effects. The first is related to the endogenous spillover model (Katsoutacos and Ulph (1998); Kultti and Takalo (1998) and Poyago-Theotoky (1999); Gersbach and Schmutzler (2003); Jin and Troege (2006) etc.). Kultti and Takalo (1998) and Poyago-Theotoky (1999) examine the three-stage game that comprises cost-reducing R&D investment (stage 1), firms' endogenous choice of R&D spillover (stage 2), and quantity competition (stage 3). In contrast to that, the game timing used for the analyses described in this paper differs from the settings of those previous studies. As described in this paper, stage 1 and stage 2 are interchanged. More precisely, Kultti and Takalo (1998) and Poyago-Theotoky (1999) consider firms' endogenous choices of the degree of R&D spillover *after the R&D stage*. The present paper explicitly examines the mechanism of endogenous R&D formation *before the environmental R&D stage*. The reason for the use of our setting is that the ERJV setup must be agreed upon *before the R&D stage*. The second point for consideration is related to the controllability of R&D spillover. Poyago-Theotoky (1999) assumes that the R&D spillover effect is perfectly controllable for each firm. However, judged from a realistic perspective, the assumption of perfect controllability is somewhat strong because some R&D spillover effects cannot be controlled by firms. Consequently, in contrast to that study, the degree of R&D spillover effects is newly defined as partially controllable.

To examine firms' endogenous choice of R&D formation and welfare performance of the four scenarios defined in Table 1, we compare two ERJV formations' equilibrium outcomes with the equilibrium outcomes of environmental R&D competition/cartelization explored by Poyago-Theotoky (2007). In the Poyago-Theotoky (2007) model, the technological spillover effect is invariably given exogenously: firms cannot control it. Consequently, this paper extends her model. Precisely speaking, we include two options of endogenous ERJV formation in which firms can set the technological spillover effect at the full level from the initial given level, but only if both firms agree on full information sharing of environmental R&D findings before the R&D stage.

In the context of policy design in an oligopolistic market, strategic interactions exist between the government and firms with market power. In the absence of a precommitment ability related to the emission tax rate, firms' environmental R&D investment can affect future

[5] As some representative studies of environmental R&D from the empirical side, see Scott (2003, 2005).

[6] This table follows Kamien et al. (1992, Table 1).

government decision-making related to emission tax policy.[7] Strictly speaking, polluting firms can have some incentives for large environmental R&D investment to elicit a lower emission tax rate from the government. The effect is designated as a *ratchet effect*.[8] The problems of timing and precommitment ability in environmental policy have been explored widely (Poyago-Theotoky and Teerasuwannajak (2002); Abrego and Perroni (2002); Requate (2005); Puller (2006), and Brunner et al. (2012)), but little attention has been devoted to the welfare performance of ERJV in the presence of a *ratchet effect*. The primary purpose of this study is to clarify that point, which remains obscure.

Our main contributions are the following. First, we demonstrate that both firms will invariably form ERJV cartelization within a symmetric R&D/Cournot model to the extent that the government completely approves R&D coordination and full information sharing under the time-consistent emission tax. Neither the ERJV competition nor environmental R&D competition/cartelization is formed spontaneously in this context. Second, although we confirm that the welfare performance of ERJV cartelization always dominates ERJV competition and environmental R&D cartelization, we also demonstrate, in sharp contrast to results of previous works, that ERJV cartelization is not necessarily socially preferable or acceptable. The welfare performance of ERJV cartelization varies with conditions of three exogenous parameters: environmental damage, cost efficiency of R&D investment, and the initial technological spillover effect. We identify the conditions in which environmental R&D competition is superior to ERJV cartelization. In other words, this article describes the frontier of policy change between environmental R&D competition and ERJV cartelization. We present a complete examination of firms' endogenous choice of environmental R&D formation under a time-consistent emission tax and present theoretical foundations for ERJV policy and firm behaviors.

This paper is presented as follows. The next section introduces the model and some preliminary points related to the evaluation of four environmental R&D formations. The third section is an exploration of the firm profitability and endogenous choice of environmental R&D formation. The fourth section presents an examination of which R&D regime has social superiority; then it presents a derivation of theoretical contributions and policy implications. The final section presents conclusions.

2. The model and some preliminary points

First, Subsection 2.1 presents the model designed to investigate the welfare performance of four environmental R&D formations defined in Table 1.[9] Second, as some preliminary points related to the derivation of new findings, Subsection 2.2 provides equilibrium outcomes under four scenarios.

2.1. The model

This paper assumes an industry comprising two homogeneous firms (firm i and firm j) engaging in a quantity competition with the same cost structure and emission-reducing technology. Then q_i denotes firm i's output. Demand is given as $p(q_i,q_j)=a-(q_i+q_j),(i,j=1,2;i\neq j)$, where $a(>0)$ is a market size parameter.

The value of each firm's emissions per unit of output is one. Firm i's environmental R&D effort is captured by z_i. Both firms use end-of-pipe technology for pollution abatement. This end-of-pipe technology mitigates (net) emissions by adsorbing pollution at the end of the production process.[10] Flue gas desulfurization equipment and activated carbon adsorption equipment are examples of end-of-pipe technology.

Firm i receives benefits not only from its own environmental R&D effort but also from the effort of its rival. When firm i's production level is q_i, then the R&D expenditure $(\gamma/2)z_i^2,(\gamma>0)$ enables firm i to abate its emissions from q_i to $e_i(q_i,z_i)\equiv q_i-z_i-\beta_j z_j$, $(i,j=1,\ 2;i\neq j)$. A lower value of γ implies higher efficiency of the R&D cost. In firm i's emission function $e_i(q_i,z_i)$, positive externalities from firm j's R&D effort are captured by $\beta_j z_j$. The R&D spillover effect from firm j to firm i is defined as follows.[11]

$$\beta_j=\begin{cases}1 & \text{if an ERJV is realized.}\\ \beta\in[0,1) & \text{otherwise.}\end{cases}$$

This paper assumes that an ERJV is realized between two firms only when both firms agree to form an ERJV before R&D investment (to choose its environmental R&D level cooperatively/non-cooperatively) and execute complete information sharing of R&D results after R&D activities. Consequently, in the case of ERJV, the value of the spillover effect is set endogenously as $\beta_i=1=\beta_j$ by both firms. The analyses described in this article are also made under the assumption that no fixed costs for ERJV are necessary. When ERJV is not realized, both firms face an exogenous spillover parameter $\beta\in[0,1)$ that is assumed to be symmetric.[12] No fixed costs for pollution abatement are necessary.[13] In addition, firm i's total cost function is additively separable with respect to production costs and R&D expenditures:$C(q_i,z_i)=cq_i+(\gamma/2)z_i^2,(c>0,A\equiv a-c>0)$.

Firm i's net emissions $e_i(q_i,z_i)$ depend on both the output and environmental R&D effort. Total emissions $E\equiv\sum_{i=1}^{2}e_i(q_i,z_i)$ cause environmental damage $D(E)\equiv(d/2)E^2$; $d(>\underline{d}\equiv(-1+\sqrt{3})/2)$ is the damage coefficient.[14] Social welfare is defined as the sum of consumers' surplus and the producers' surplus less environmental damage and total R&D expenditures.

In this model, the government has policy instruments of two types. One is competition policy: a combination of ERJV policy and approval/disapproval of R&D coordination. At the first stage, the government decides according to a *rule of reason* whether an ERJV is socially prohibited, and also whether R&D coordination is socially allowable. The other role

[7] We assume that the regulator is unable to commit to a fixed emission tax policy (i.e., no precommitment ability) in this environmental R&D context. A reviewer, however, pointed out that the assumption might seem to be in direct opposition to the idea of binding international agreements to limit greenhouse gas emissions with some expectation that those agreements are binding. The reviewer also pointed out this issue can be resolved by framing the precommitment issues in terms of the long-run vs. short-run. Policy is apparently fixed in the short-run, but in the long-run, regulators cannot precommit for the next round of international negotiations. If the R&D time-horizon is of approximately the long-run, then the no-precommitment assumption is reasonable. Actually, we established that each firm's cost function has no fixed cost. Therefore, implicitly, we assume a long-run situation.

[8] For detailed discussions about the *ratchet effect*, see Hepburn (2006, Section 5); Puller (2006), and Brunner et al. (2012, Subsubsection 3.1.3).

[9] Whereas the current model fundamentally follows the Poyago-Theotoky (2007) model, the setting of this article includes the Poyago-Theotoky model for subgames. See also footnote 16.

[10] This end-of-pipe technology does not change initial (gross) emissions per unit of output, but it can reduce final (net) emissions at the end-of-pipe.

[11] This setting differs from existing endogenous spillover models (e.g., Kultti and Takalo (1998); Poyago-Theotoky (1999), and Jin and Troege (2006)). In a different context from ours, Poyago-Theotoky (1999) assumes that the degree of spillover is perfectly controllable for each firm. However, in our real society, it would not be an exaggeration to state that there invariably exist some R&D spillover effects that firms cannot control. For that reason, we assume that β_i is partially controllable for firm i.

[12] For details of R&D spillover, see Griliches (1992) and Goel and Haruna (2007, Section 1). For a model of technological spillovers in the context of international environmental R&D, see El-Sayeda and Rubio (2014).

[13] Most existing incumbents in the chemical products industry have installed emission-reducing equipment of the end-of-pipe type. Such investments in quality-improvement of desulfurization and hydrodenitrogenation catalysts are applicable to this model because no fixed set-up cost for abatement is required. In contrast to this model, the installation of a new abatement technology incurs a fixed set-up cost (see Requate and Unold (2003)).

[14] An interior solution for R&D stage is guaranteed by this assumption (see Ouchida and Goto (2011)). Exogenous parameter d should be derived from the findings of environmental epidemiology and public health. In fact, population accumulation, depopulation, and pollutant toxicity can affect d. The value of $d\in(\underline{d},+\infty)$ which describes various market circumstances can be plausible. Hence, more interdisciplinary studies must be conducted to produce effective ERJV guidelines. Antelo and Loureiro (2009, p.1432) regard d as "the regulator's valuation of the environment, or the regulator's preferences with respect to the redistribution of environmental damage."

is emission tax policy. This study assumes that the government has no precommitment ability for an emission tax rate t. Consequently, the tax rate is set to maximize social welfare after firms' environmental R&D investment at stage 2.[15] The time structure is the following.[16]

Stage 1: The government decides whether to prohibit an ERJV between two firms, or not, and also whether R&D coordination is permitted.

Each firm's strategy set at the second stage depends on the government's decision-making at stage 1. All potentialities for a firm's strategy set at stage 2 are the following four cases.

[1] When the government prohibits both ERJV and R&D coordination, each firm's strategy set at stage 2 is {N}.
[2] When the government allows ERJV, and when it prohibits R&D coordination, firms i and j $(i \neq j)$ respectively choose their own R&D formations s_i and s_j from the strategy set {N, NJ} at stage 2.
[3] When the government prohibits ERJV, and when permitting R&D coordination, firms i and j $(i \neq j)$ respectively choose their own R&D formations s_i and s_j from the strategy set {N, C} at stage 2.
[4] When the government allows both of ERJV and R&D coordination, firms i and j respectively choose their own R&D formations s_i and s_j from the strategy set {N, C, NJ, CJ} at stage 2.

Stage 2: From the strategy set corresponding the result of government's decision-making at stage 1, firms i and j respectively choose their own R&D formations s_i and s_j simultaneously. The resulting R&D formation is generated by the following rules.

- When $(s_i, s_j) = (\mathrm{C}, \mathrm{C})$, then case C is realized.
- When $(s_i, s_j) = (\mathrm{NJ}, \mathrm{NJ})$, then case NJ is realized.
- When $(s_i, s_j) = (\mathrm{CJ}, \mathrm{CJ})$, then case CJ is realized.
- When $(s_i, s_j) = (\mathrm{N}, \mathrm{N})$ or $s_i \neq s_j$, then case N is realized.

Stage 3: Each firm chooses its environmental R&D effort level.
Stage 4: The regulator sets the emission tax rate to maximize social welfare.
Stage 5: Firm i sets its output level non-cooperatively to maximize its own profit.

2.2. Equilibrium outcomes

The solution concept used here is the subgame-perfect Nash equilibrium (SPNE). The five-stage game explained above is solved by backward induction. Appendix A presents the examinations of subgames: stages 3, 4, and 5. A brief sketch of solution procedures under four scenarios defined in Table 1 and results are provided in Appendix A and Table A1. Furthermore, we summarize the existence of equilibrium outcomes under four scenarios as the following Lemma.

Lemma 1.

(i) *There exist unique equilibrium outcomes in cases N and C, respectively.*
(ii) *If both firms form an ERJV with full information sharing of R&D results, which is characterized by endogenous setting $\beta_i = 1 = \beta_j$, then there exist unique equilibrium outcomes in case NJ and CJ, respectively.*

Proof.

(i) See Poyago-Theotoky (2007, Section 2). □
(ii) See Appendix A of this paper and Poyago-Theotoky (2007, Section 2). The equilibrium outcomes under ERJV competition (cartelization) are produced from the equilibrium values of environmental R&D competition (cartelization) case after setting $\beta_i = 1 = \beta_j$. □

3. Firm profitability and endogenous choice of R&D formation

We analyze each firm's choice of environmental R&D formation at stage 2. In Subsection 2.1, the time structure of the game is explained. We have understood that, as a result of the government decision-making during the first stage, four potential circumstances exist.

First, if neither ERJV nor R&D coordination is allowed, then the only lawful R&D formation is R&D competition (case N). Then, each firm obtains π_{N}. Second, if each firm faces with the strategy set {N, NJ}, then they compare π_{N} with π_{NJ}. We readily obtain that $\pi_{\mathrm{NJ}} > \pi_{\mathrm{N}}$. Third, if each firm has the strategy set {N, C}, then they compare π_{N} with π_{C}. With regard to private incentives for R&D cooperation, Poyago-Theotoky (2007, p.70) shows that $\pi_{\mathrm{C}} > \pi_{\mathrm{N}}$.[17]

Next, we examine the fourth potentiality. If each firm faces the strategy set {N, C, NJ, CJ}, then it compares four equilibrium profits: π_{N}, π_{C}, π_{NJ}, and π_{CJ}. Eq. (16) of Poyago-Theotoky (2007, p.70) straightforwardly demonstrates that $\pi_{\mathrm{CJ}} > \pi_{\mathrm{NJ}}$ when $\beta_i = 1 = \beta_j$. That study implies that ERJV competition (case NJ) is not implemented. Furthermore, π_{N} is dominated by π_{C}. Consequently, to derive new contributions, we specifically examine π_{CJ} and π_{C}. Comparison of the equilibrium profit under ERJV cartelization, π_{CJ}, with that under environmental R&D cartelization, π_{C} shows that $\pi_{\mathrm{CJ}} > \pi_{\mathrm{C}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0, 1)$. From the discussion presented above, we have $\pi_{\mathrm{CJ}} > \pi_{\mathrm{C}} > \pi_{\mathrm{N}}$ and $\pi_{\mathrm{CJ}} > \pi_{\mathrm{NJ}} > \pi_{\mathrm{N}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0, 1)$. Consequently, these show that ERJV cartelization is most preferred for each firm.

Proposition 1 summarizes results related to a firm's choice of R&D formation.

Proposition 1.

(i) *When both ERJV and R&D coordination are socially prohibited, then environmental R&D competition is the only feasible formation.*
(ii) *When ERJV is socially allowable, and when R&D coordination is socially prohibited, then both firms prefer ERJV competition to environmental R&D competition.*
(iii) *When ERJV is socially prohibited, and when R&D coordination is socially allowable, then both firms prefer environmental R&D cartelization to environmental R&D competition.*
(iv) *When both ERJV and R&D coordination are socially allowable, then both firms prefer ERJV cartelization to any other scenario.*

Proof. See S.1 of Supplementary material (Appendix C). □

The investigations explained above demonstrate that ERJV cartelization between symmetric Cournot duopolists always yields the greatest profitability among four scenarios. This new result is derived from examinations under our endogenous choice model of environmental R&D formation. Therefore, both firms invariably carry out ERJV cartelization at stage 2 unless it is prohibited. The intuitive explanation here is given as follows. Forming an ERJV (i.e., $\beta_i = 1 = \beta_j$) generates the strongest free-riding effect.[18] Moreover, R&D coordination internalizes

[15] The choice of timing of the game depends on precommitment ability for the tax rate. If the regulator has such ability, he can set the tax rate before R&D stage. Ouchida and Goto (2016) examined cases in which the regulator has precommitment ability. Results show that environmental R&D cartelization is always socially more efficient than environmental R&D competition. Moreover, ERJV cartelization is socially the most efficient.

[16] Whereas stages 3, 4, and 5 in this paper are identical to the three-stage game developed by Poyago-Theotoky (2007), stages 1 and 2 are newly added for the analyses described in this paper.

[17] For the proofs of $\pi_{\mathrm{NJ}} > \pi_{\mathrm{N}}$ and $\pi_{\mathrm{C}} > \pi_{\mathrm{N}}$, see S.1 of Supplementary material.

[18] For an explanation of the free-riding effect, see Eq. (A.2). In (A.2), $(\partial t / \partial z_i) \beta z_j$ denotes the free-riding effect.

free-riding effects between two firms, and also increases the marginal profit from environmental R&D investment.

4. R&D regimes and social superiority

Next we explore the government's decision-making at stage 1. With respect to the equilibrium social welfare presented in Table A1, from Poyago-Theotoky's (2007) investigation, it can be understood that $SW_{\mathrm{CJ}}>SW_{\mathrm{NJ}}$.[19] That is, the equilibrium social welfare under ERJV cartelization dominates that under ERJV competition. Therefore, the government has no social incentive for ERVJ competition. Hereinafter, we do not analyze the case of ERJV competition. Instead, we concentrate on the welfare performance of the other R&D regimes. This section presents an examination of whether equilibrium social welfare under ERJV cartelization dominates that under the other two R&D scenarios: environmental R&D competition and environmental R&D cartelization.

4.1. Environmental R&D cartelization versus ERJV cartelization

Comparing equilibrium social welfare under environmental R&D cartelization, SW_{C}, with that under ERJV cartelization, SW_{CJ}, engenders the following proposition.

Proposition 2. *$SW_{CJ}>SW_C$ for all $d>\underline{d}$, $\gamma>0$ and $\beta\in[0,1)$.*

Proof. See S.2 of Supplementary material (Appendix C). □

This proposition states that, in terms of social-welfare maximization, ERJV cartelization invariably dominates the case of environmental R&D cartelization. Full information sharing generates welfare superiority compared with the case of R&D cartelization. This result is consistent with our intuition.

4.2. Environmental R&D competition versus ERJV cartelization

First, as a baseline of our analysis, we can set the curve provided in Poyago-Theotoky (2007, p71). We designate it as γ_φ. In the region above (below) the curve γ_φ in Fig. 1, $SW_{\mathrm{C}}\geq(<)SW_{\mathrm{N}}$ and $z_{\mathrm{C}}\geq(<)z_{\mathrm{N}}$.[20] In addition, when the degree of spillover is perfect (i.e., $\beta_i=1=\beta_j$), then $SW_{\mathrm{CJ}}>SW_{\mathrm{NJ}}$.

We now compare the two equilibrium social welfare levels: SW_{CJ} and SW_{N}. The difference between them is given as shown below.

$$SW_{\mathrm{CJ}}-SW_{\mathrm{N}}=\frac{J(d,\gamma;\beta)A^2}{\underline{\Delta}^2\Gamma^2}\gtrless 0. \tag{1}$$

S.3 of Supplementary material (Appendix C) presents details of Eq. (1). Fig. 1 presents a graphical analysis of this comparison.

Specific examination of the case of imperfect spillover (i.e., $\beta_i=\beta_j=\beta<1$) reveals some interesting findings: When $\underline{d}<d\leq 3/2$, then $J(d,\gamma;\beta)\geq 0$; ERJV cartelization is invariably socially superior to environmental R&D competition, irrespective of the value of γ. However, if $d>3/2$, then ERJV cartelization is superior (inferior) to environmental R&D competition for all $\gamma\geq(<)\gamma_{JV}\equiv\{\gamma(>0)|J(d,\gamma;\beta)=0,d>3/2\}$.[21] In the region above (below) the curve γ_{JV} in Fig. 1, $SW_{\mathrm{CJ}}\geq(<)SW_{\mathrm{N}}$. These new findings are summarized as Proposition 3.

Proposition 3.

(i) *If $\underline{d}<d\leq 3/2$, then $SW_{CJ}\geq SW_N$ for all $\gamma>0$ and $\beta\in[0,1)$.*
(ii) *If $d>3/2$ and $\gamma\geq\gamma_{JV}$, then $SW_{\mathrm{CJ}}\geq SW_{\mathrm{N}}$ for all $\beta\in[0,1)$.*
(iii) *If $d>3/2$ and $\gamma<\gamma_{JV}$, then $SW_{\mathrm{CJ}}<SW_{\mathrm{N}}$ for all $\beta\in[0,1)$.*

Poyago-Theotoky (2010) points out that negative emission taxes (emission subsidies) might be socially justified. When the value of d is in the interval $(\underline{d},3/2)$ and the value of γ is strictly smaller than the critical value $\gamma_{\mathrm{CJ}}^t\equiv 4d(3-2d)/(2d^2+d-1)$, then the regulator can mitigate market inefficiency through emission subsidies and ERJV cartelization irrespective of the value of the spillover parameter.[22] In fact, in Region I below the curve γ_{CJ}^t in Fig. 1, one can observe that $t_{\mathrm{CJ}}<0$ and $SW_{\mathrm{CJ}}>SW_{\mathrm{C}}>SW_{\mathrm{N}}$.[23] Propositions 2 and 3 show that, even in the case of ERJV cartelization, not only its desirability but also a negative emission tax (emission subsidy) might be socially justified. However, only when $\gamma<\gamma_{\mathrm{N}}^t(<\gamma_{\mathrm{CJ}}^t)$, then $t_{\mathrm{N}}<0$.[24] Therefore, in Region IV below the curve γ_{JV}, the value of t_{N} is always positive. In Fig. 1, Regions II and III respectively denote the region between γ_{CJ}^t and γ_φ, and the region between γ_φ and γ_{JV}. Whereas Poyago-Theotoky (2007) shows that γ_φ represents the borderline of sign$\{SW_{\mathrm{C}}-SW_{\mathrm{N}}\}$, the existence of γ_{JV}, which plays key roles in Proposition 3, is newly revealed by this research. As Fig. 1 clarifies, when $\beta_i=1=\beta_j$, then Regions III and IV disappear (see S.3 of Supplementary material and footnote 20).

Table 2 presents the welfare ranking and the sign of an emission tax rate in each region of Fig. 1. Fig. 1 and Table 2 show that, in Regions I, II, and III, the implementation of ERJV cartelization yields improvement in social welfare. However, particularly addressing the existence of Region IV, it seems clear that ERJV cartelization is not necessarily better than in any other scenario. Particularly with a small value of γ, $(\gamma<\gamma_{JV})$, and a large value of d, $(d>3/2)$, environmental R&D competition is socially better.[25] In other words, part (iii) of Proposition 3 shows that ERJV cartelization is socially harmful in Region IV. Therefore, it is apparent that a social incentive for ERJV cartelization does not always exist. Furthermore, to reveal the difference of emission reducing effect, we examine what scenario generates the lowest emissions. By comparing four equilibrium emissions (e_{N}, e_{C}, e_{NJ}, and e_{CJ}) presented in Table A1, we obtain that the lowest total emission is yielded under case CJ for all $d>\underline{d}$, $\gamma>0$ and $\beta\in[0,1)$.

The reason for the existence of Region IV can be interpreted as follows. Greater R&D efforts decrease the emission tax rate chosen during the fourth stage.[26] In papers by Hepburn (2006); Puller (2006), and Brunner et al. (2012), this decrease is designated as a "*ratchet effect*." If the value of γ is small, then the joint-profit maximization effect is dominated by the profit-enhancing effect through the *ratchet effect*. For that reason, there can exist circumstances such that $z_{\mathrm{CJ}}<z_{\mathrm{N}}$.[27] Greater environmental R&D efforts increase production levels and consumer surplus. When the damage is severe and when R&D costs are highly

[19] See Eq. (14), Corollary 1 and Proof of Proposition 2 in Appendix A in Poyago-Theotoky (2007). In her analysis, ERJVs are not examined as the central question. Strictly speaking, she demonstrates that $SW_{\mathrm{C}}|_{\beta=1}>SW_{\mathrm{N}}|_{\beta=1}$ in the special case in which the value of exogenous parameter β is one.

[20] The definition of φ is given by Poyago-Theotoky (2007, p.69). The definition of γ_φ is $\gamma_\varphi\equiv\{\gamma>0|\varphi\equiv d(3-2d)(1+\beta)^2(1-\beta)+2\gamma(2d^2\beta+2d\beta-\beta+d)=0,d>3/2\}$. The curve γ_φ has the following property: $\lim_{d\to+\infty}\gamma_\varphi=(1+\beta)^2(1-\beta)/2\beta$. Results show that when $\beta_i=1=\beta_j$, then γ_φ disappears. Her investigation reveals that sign$\{\varphi\}=$ sign$\{z_{\mathrm{C}}-z_{\mathrm{N}}\}=$ sign$\{SW_{\mathrm{C}}-SW_{\mathrm{N}}\}$.

[21] It is straightforward to verify the existence and uniqueness of γ_{JV}. However, it is extremely difficult to obtain γ_{JV} explicitly by solving the cubic equation $J(d,\gamma;\beta)=0$.

[22] Critical value $\gamma_{\mathrm{CJ}}^t\equiv 4d(3-2d)/(2d^2+d-1)$ is derived from $t_{\mathrm{CJ}}=0$.

[23] Our companion paper (Ouchida and Goto (2014)) reveals the emission-reducing effects of negative emission taxes (i.e., emission subsidies). That study is very closely related to the investigations conducted by this paper. For details, see Proposition 2 and Fig. 1(iv) in Ouchida and Goto (2014).

[24] The critical value $\gamma_{\mathrm{N}}^t\equiv d(3-2d)(1+\beta)^2/2(2d^2+d-1)$ is derived from $t_{\mathrm{N}}=0$.

[25] The critical value of the parameter capturing the R&D efficiency, γ_{JV}, can be interpreted as the threshold that indicates for the regulator the environmental R&D formation to approve when the damage is severe.

[26] See Eq. (A.1) in Appendix A. In fact, one obtains that $\partial t(z_i,z_j)/\partial z_i<0$.

[27] Appendix B proves the mechanism of $z_{\mathrm{CJ}}<z_{\mathrm{N}}$ through comparison of the profit enhancing effect and the joint profit maximization effect. In fact, a comparison between z_{CJ} and z_{N} yields the following result: $z_{\mathrm{CJ}}\geq(<)z_{\mathrm{N}}$ for all $\gamma\geq(<)\hat{\gamma}_N\equiv d(1-\beta)\delta/\mu$, where $\mu\equiv(1+d)^2[2d^2+(4-\beta)d-1](>0)$ and $\delta\equiv 18d^3+41d^2+12d-15+\beta(d+3)(d^2+3d-1)(>0)$. Therefore, if γ is small $(\gamma<\hat{\gamma}_{\mathrm{N}})$, then $z_{\mathrm{CJ}}<z_{\mathrm{N}}$. This result differs from the result reported by d'Aspremont and Jacquemin (1988, 1990), which showed that cost-reducing R&D efforts under RJV cartelization are invariably greater than under any other scenario. This result implies that the case of ERJV cartelization does not always yield larger investments than under any other scenario presented in Table 1.

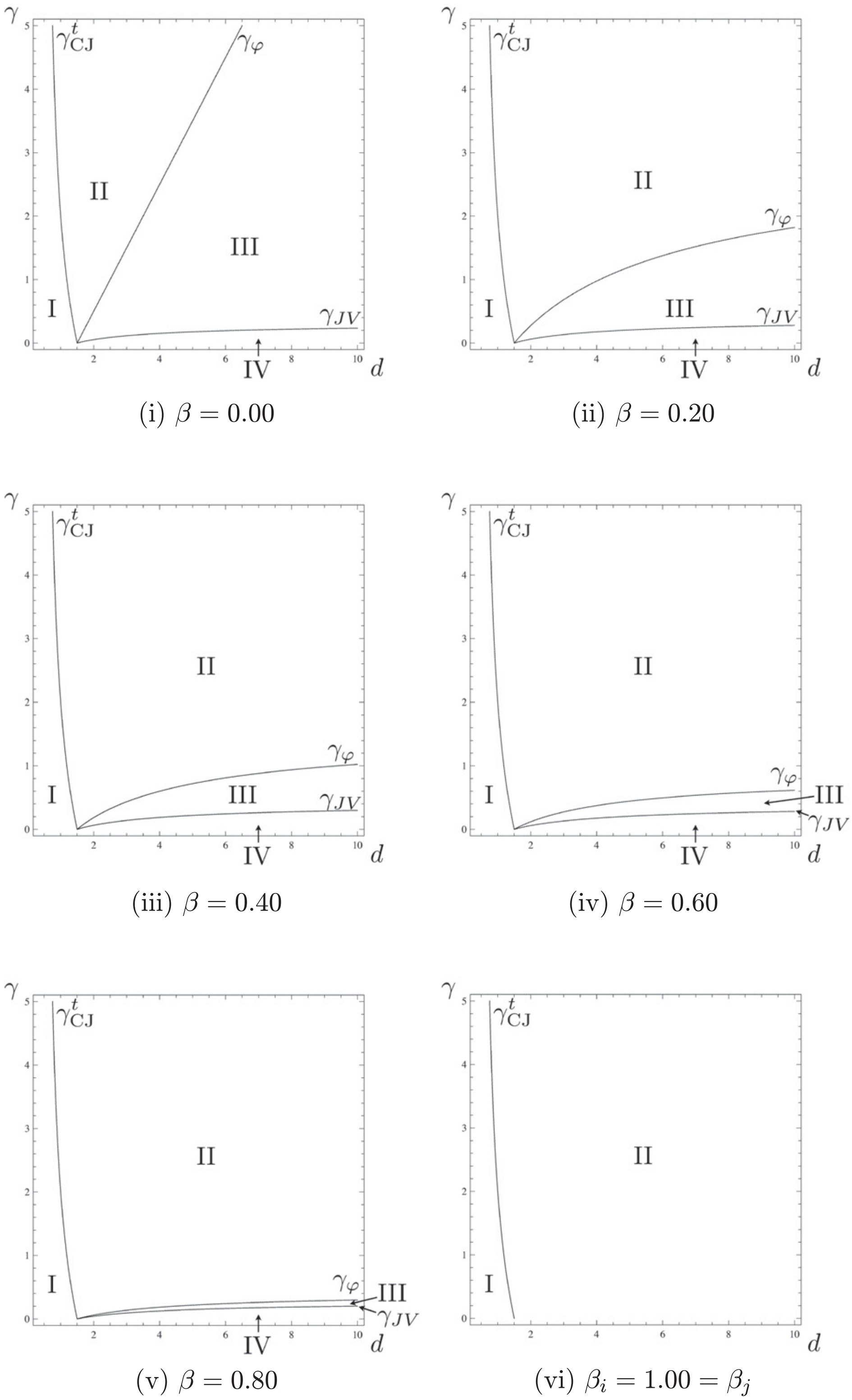

Fig. 1. Environmental R&D competition versus ERJV cartelization.

efficient, greater R&D efforts generated through R&D competition produce large increase effects on consumer surplus and a large mitigating effect on environmental damage. These effects dominate the increasing effects of R&D costs. Therefore, the equilibrium social welfare under environmental R&D competition is greater than in the case of ERJV cartelization. However, when the damage coefficient is small ($d < 3/2$), the equilibrium social welfare under environmental R&D competition is dominated by that under ERJV cartelization because of the slight mitigating effect of environmental damage.

4.3. Theoretical contributions

This article presents development of an analytical framework of endogenous choice of environmental R&D formation. The game-theoretic

Table 2
Welfare ranking and the sign of the emission tax rate.

Region	Emission tax	Welfare ranking
I	$t_{CJ}<0$	$SW_{CJ}>SW_C>SW_N$
II	$t_{CJ}>0$	$SW_{CJ}>SW_C>SW_N$
III	$t_{CJ}>0$	$SW_{CJ}>SW_N>SW_C$
IV	$t_N>0$	$SW_N>SW_{CJ}>SW_C$

setting of this paper enables evaluation of the welfare performance of four scenarios (in Table 1). Under the settings, two theoretical findings are obtained.

The first finding is that each firm invariably has a private incentive for ERJV cartelization (Proposition 1(iv)). The second finding is that ERJV cartelization does not necessarily engender social efficiency (Propositions 2 and 3). More precisely, in Regions I, II, and III in Fig. 1, ERJV cartelization is socially beneficial and feasible. However, in Region IV, firms cannot receive both profits under ERJV competition/cartelization (π_{NJ} and π_{CJ}) because the welfare-maximizing regulator can accommodate neither information sharing nor R&D coordination, whereas firms prefer ERJV cartelization.

These findings justify that the stages of government's competition policy and firm's endogenous choice of R&D formation are necessary. In other words, the indispensability of examinations of stages 1 and 2 in the present model is proved by the results of Propositions 2 and 3. In the previous studies, neither stage has been analyzed explicitly despite the existence of firms' private incentives for ERJV cartelization. Instead, this article presents development of the five-stage game by adding stages of a government's competition policy (stage 1) and firms' endogenous choices of R&D formation (stage 2) to the Poyago-Theotoky three-stage model, and also provides complete examinations.

To enrich the theoretical argument in relation to competition policy in the environmental innovation area, it is important to compare our result with those of reports of the cost-reducing R&D literature that do not incorporate fixed cost for RJV. The welfare ranking in Region IV is inconsistent with findings reported by d'Aspremont and Jacquemin (1988, 1990); Atallah (2005a) and Lambertini and Rossini (2009) and others, who show the social superiority of RJV cartelization.[28] The result of Proposition 3(iii) differs greatly from the results presented in a typical textbook (Belleflamme and Peitz (2010, pp. 498–499)), demonstrating that RJV cartelization yields socially superior performance to that obtained through non-cooperative R&D. Moreover, from the perspective of RJV cost, Vilasuso and Frascatore (2000) show that R&D competition can generate higher social welfare than RJV cartelization can, but *only when the cost for forming RJV is sufficiently high*.[29] In sharp contrast to their study, Proposition 3(iii) of this paper reveals that environmental R&D competition can yield greater social welfare than ERJV cartelization can *even though the assumption of ERJV costs is unnecessary*.

[28] Atallah (2005a, p.933) examines the case of asymmetric spillover. His analysis includes results of the case of symmetric perfect spillover. Therefore, it is easy to ascertain the social superiority of RJV cartelization under symmetric perfect spillover. In addition, for details of the well-known R&D models by d'Aspremont and Jacquemin (1988, 1990) and Kamien et al. (1992), see reports by Amir (2000b) and Amir et al. (2003). Furthermore, in the literature related to cost-reducing innovation, some studies reveal that industry-wide RJV cartelization is not necessarily socially preferred. As examples, see Yin (1999); Amir (2000a), and Yun et al. (2000). The models constructed in those studies differ from the model presented here.

[29] Most reports of the cost-reducing R&D literature have examined models without a fixed cost for RJV. However, studies by Vilasuso and Frascatore (2000); Lambertini et al. (2002), and Falvey et al. (2013) are exceptional. Particularly Vilasuso and Frascatore (2000) built the first model incorporating an exogenous fixed cost for forming a RJV. Both models built by Lambertini et al. (2002) and Falvey et al. (2013) are starkly different from our model.

4.4. Policy implications

This paper presents the possibility of the superiority of ERJV cartelization. In Regions I, II, and III shown in Fig. 1, no intervention for ERJV cartelization is necessary. However, in stark contrast to the well-known result of cost-reducing R&D, we infer that environmental R&D competition is socially preferred when pollution abatement is highly cost-efficient ($\gamma<\gamma_{JV}$), and also when environmental damage is severe ($d>3/2$). In Region IV in Fig. 1, the government should allow neither information sharing nor R&D coordination.

The category of pollution abatement technology in this model is called "end-of-pipe." Measures of this category achieve reduction of the amount of emissions by absorption at the end of production processes. Flue gas desulfurization equipment and activated carbon adsorption equipment are examples of this type. As an example of the oligopolistic market corresponding to this model, we can mention oil refining firms and firms with huge chemical plants. In fact, such oligopolistic firms use end-of-pipe technology and also invest in R&D for quality improvement of catalysts. The results presented in this paper provide important and indispensable policy implications related to whether ERJV cartelization in a horizontal relation is socially beneficial.

5. Concluding remarks

This paper presents a new analytical framework of environmental R&D formation. In contrast to reports of the related literature, each firm chooses the environmental R&D formation endogenously before the R&D investment stage. Furthermore, in our five-stage game, an ERJV is realized only when two firms agree to form an ERJV before R&D investment, and agree to execute complete information sharing of R&D results after R&D investment. Under the setup and time-consistent emission taxation, this paper presents evaluation of the welfare performance of four environmental R&D formations and examines the government's competition policy.

Our analysis obtains the following facts and policy implications. If environmental damage is severe, and if the parameter of environmental R&D cost is sufficiently small, then environmental R&D competition is socially preferred. It is particularly interesting that our analysis reveals the social superiority of environmental R&D competition, although that scenario is the case of "NO information sharing and NO R&D coordination." Under such circumstances, the antitrust authorities should disallow not only ERJV cartelization but also environmental R&D cartelization. This result is fairly counterintuitive and differs from the well-known conclusions reported in the existing literature. However, if environmental damage is slight, or if severe damage and high inefficiency of environmental R&D costs exist, then ERJV cartelization is socially preferred. Under those circumstances, firms should be allowed to form an ERJV cartelization. Such cooperative behavior yields improved social welfare. Furthermore, each firm invariably has a private incentive for ERJV cartelization. Our results can considerably enrich future RJV studies in environmental areas, although only a few ERJV studies have been made heretofore.

During the last two decades, although the importance of environmental R&D has been increasingly socially recognized, a few studies have examined the welfare performance of ERJV.[30] To design appropriate environmental R&D policy, detailed and practical policy suggestions on ERJV are desired by policymakers of many countries. As an example, the Japanese antitrust guidelines for RJV (Japan Fair Trade Commission [JFTC] (1993) and its amended versions) are ambiguous and frail. Unfortunately, Japanese antitrust authorities (JFTC) have formed detailed policy guidelines for ERJV only to a slight degree. This fact signifies that the Japanese antitrust authorities' discretionary power on ERJV is too strong. Under such regulatory circumstances, ERJV participants

[30] For example, see Katsoulacos et al. (2001).

might be faced with the risk of becoming a noncompliant (or administratively sanctioned) firm involuntarily because the rules are not enacted definitely. In addition, the lack of detailed rules might generate a disincentive to forming an ERJV. This research provides theoretical findings to improve such shortcomings of present systems.

Some directions for future research seem promising. First, the case of an asymmetric spillover parameter must be analyzed in line with Atallah's (2005a, 2005b, 2007) examinations. Second, it is necessary to explore the case of a Cournot oligopoly market with socially responsible firm (see Lambertini and Tampieri (2015)). Third, some examination of a time-consistent emission tax policy should be conducted in a setting where abatement goods and services are provided by an eco-industry (see David and Sinclair-Desgagné (2010) and David et al. (2011)).

Appendix A

This Appendix provides a brief outline of solution procedures for seeking SPNE under the four scenarios defined in Table 1 and equilibrium outcomes (Table A1).

A.1. Environmental R&D competition

In this case, neither firm forms an ERJV or coordinates the R&D effort level. In the last stage, firm *i*'s profit is

$$\pi_i\left(q_i,q_j\right) = \left\{a-\left(q_i+q_j\right)\right\}q_i - cq_i - t\{q_i - z_i - \beta z_j\} - (\gamma/2)z_i^2.$$

Each firm decides its own output level non-cooperatively and simultaneously. From the first-order conditions for profit maximization, the symmetric equilibrium output is derived as $q(t) = (A-t)/3$.

Consequently, social welfare in stage 4 is calculated as

$$SW(t) = 2Aq(t) - 2[q(t)]^2 - (d/2)\{2q(t) - (1+\beta)\{z_i + z_j\}\}^2 - \sum_{i=1}^{2}(\gamma/2)z_i^2.$$

The regulator sets the emission tax rate to maximize social welfare.[31] From the first-order condition for social welfare maximization, the subgame equilibrium tax rate is obtained as

$$t(z_i,z_j) = \frac{(2d-1)A - 3d(1+\beta)\{z_i+z_j\}}{2(1+d)}. \tag{A.1}$$

Therefore, firm *i*'s profit during the third stage is

$$\pi_i(z_i,z_j) = \left[q(t(z_i,z_j))\right]^2 + t(z_i,z_j)\{z_i+\beta z_j\} - (\gamma/2)z_i^2.$$

Each firm non-cooperatively and simultaneously sets its environmental R&D effort. The first-order conditions for profit maximization is

$$\frac{\partial \pi_i(z_i,z_j)}{\partial z_i} = 2\left[\frac{\partial q}{\partial t}\right]\left[\frac{\partial t}{\partial z_i}\right] + \left[\frac{\partial t}{\partial z_i}\right]z_i + \left[\frac{\partial t}{\partial z_i}\right]\beta z_j + t(z_i,z_j) - \gamma z_i = 0. \tag{A.2}$$

Therein, $i,j = 1,2; i \neq j$. These conditions generate the following equilibrium R&D efforts.[32]

$$z_N = \frac{[(1+d)(2d-1) + d(1+\beta)]A}{2\gamma(1+d)^2 + d(1+\beta)[3(3+\beta) + d(7+\beta)]}.$$

The equilibrium levels of the emission tax rate, output level for each firm, profit, and social welfare are presented in Table A1.

A.2. Environmental R&D cartelization

Solution procedures of stages 4 and 5 are identical to those in Subsubection 2.2.1. However, environmental R&D cartelization implies that two firms do not form an ERJV, but they cooperatively and simultaneously set their environmental R&D efforts to maximize joint profits $\Pi \equiv \pi_i(z_i,z_j) + \pi_j(z_i,z_j)$ during the third stage.[33] Then, the equilibrium levels of the equilibrium outcomes are derived in Table A1.

A.3. ERJV competition

In this case, both firms form an ERJV to avoid duplication of R&D activities and share all R&D information, but they do not coordinate the R&D effort level. When the ERJV is formed, each firm chooses perfect technological spillover. Full sharing of the results of R&D are characterized by $\beta_i = 1 = \beta_j$, although the value of β is exogenous in the previous two cases. The equilibrium outcomes under ERJV competition are produced from the equilibrium values of environmental R&D competition case after setting $\beta_i = 1 = \beta_j$. The results are presented in Table A1.

A.4. ERJV cartelization

In this case, both firms form an ERJV to avoid duplication of R&D activities. During the third stage, they coordinate the R&D effort level to maximize joint profits: $\Pi(z_i,z_j;\beta_i = 1 = \beta_j) \equiv \pi_i(z_i,z_j;\beta_i = 1) + \pi_j(z_i,z_j;\beta_j = 1)$. In addition, sharing of the results of R&D is fully conducted. As in the case of ERJV competition, two firms set $\beta_i = 1 = \beta_j$. The equilibrium outcomes under ERJV cartelization are derived from the equilibrium values of environmental R&D cartelization case after setting $\beta_i = 1 = \beta_j$. Results are calculated in Table A1.

[31] In the case of precommitment to an emission tax rate, emissions' taxation (in general) induces pollution abatement via an (1) output effect and a (2) substitution effect. The output effect arises as the tax raises the (relative) price of the dirty good, leading to a lower quantity demanded by consumers. The substitution effect induces the dirty good producer to lower net emissions to maximize profit. Consequently, the firms are engaging in environmental R&D in an effort to satisfy this substitution effect and to lower net emissions. In our time-consistent emission tax model, neither firm knows the emission tax rate before the environmental R&D stage because the tax rate is not precommitted. However, before the R&D stage, each firm knows that the government introduces emissions' taxation. Consequently, emission abatement is conducted through the output effect and substitution effect in a time-consistent emission tax model as well as the precommitted emission tax model.

[32] Under case N, we obtain $(\partial^2\pi_i/\partial z_i^2)(\partial^2\pi_j/\partial z_j^2) - (\partial^2\pi_i/\partial z_i\partial z_j)(\partial^2\pi_j/\partial z_j\partial z_i) = I_1/(4(1+d)^2) > 0$, where $I_1 \equiv 3(1-\beta)(1+\beta)^2d^2(1+d)[9+7d+\beta(3+d)] + 4(1+\beta)d[6+(5-\beta)d]\gamma + 4(1+d)^2\gamma^2 > 0$ for all $d > \underline{d}, \gamma > 0$ and $\beta \in [0,1)$. Therefore, the Routh–Hurwitz condition for local stability is invariably satisfied.

[33] Under case C, we have $(\partial^2\Pi/\partial z_i^2)(\partial^2\Pi/\partial z_j^2) - (\partial^2\Pi/\partial z_i\partial z_j)(\partial^2\Pi/\partial z_j\partial z_i) = I_2/(3(1+d)^4) > 0$, where $I_2 \equiv (1+\beta)^4d^3(6+5d) + 2(1+\beta)^2d(1+d)^2(9+8d)\gamma + 3(1+d)^4\gamma^2 > 0$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0,1)$. Therefore, the Routh–Hurwitz condition for local stability is invariably satisfied.

Table A1
Equilibrium outcomes under four scenarios.

	Environmental R&D competition (case N)	Environmental R&D cartelization (case C)
Environmental R&D efforts	$z_N = \frac{[(1+d)(2d-1)+d(1+\beta)]A}{2\gamma(1+d)^2+d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$z_C = \frac{(1+\beta)[(1+d)(2d-1)+2d]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Emission tax rate	$t_N = \frac{[d(2d-3)(1+\beta)^2+2\gamma(2d^2+d-1)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$t_C = \frac{[d(2d-3)(1+\beta)^2+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Output level	$q_N = \frac{[2(1+d)\gamma+d(1+\beta)(7+4d+3\beta)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$q_C = \frac{[d(5+2d)(1+\beta)^2+\gamma(1+d)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Emission	$e_N = \frac{[2(1+d)\gamma+(1+\beta)\{(3+\beta)d+2\}]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$e_C = \frac{[(1+d)\gamma+(2d+1)(1+\beta)^2]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Profits	$\pi_N = q_N^2 + t_N(1+\beta)z_N - (\gamma/2)z_N^2$	$\pi_C = q_C^2 + t_C(1+\beta)z_C - (\gamma/2)z_C^2$
Social welfare	$SW_N = 2Aq_N - 2q_N^2 - 2d\{q_N-(1+\beta)z_N\}^2 - \gamma z_N^2$	$SW_C = 2Aq_C - 2q_C^2 - 2d\{q_C-(1+\beta)z_C\}^2 - \gamma z_C^2$
	ERJV competition (case NJ)	ERJV cartelization (case CJ)
Environmental R&D efforts	$z_{NJ} = \frac{(2d^2+3d-1)A}{2\gamma(1+d)^2+8d(3+2d)}$	$z_{CJ} = \frac{(2d^2+3d-1)A}{\gamma(1+d)^2+8d(3+2d)}$
Emission tax rate	$t_{NJ} = \frac{[2d(2d-3)+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$t_{CJ} = \frac{[4d(2d-3)+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Output level	$q_{NJ} = \frac{[(1+d)\gamma+2d(5+2d)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$q_{CJ} = \frac{[4d(5+2d)+\gamma(1+d)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Emission	$e_{NJ} = \frac{[(1+d)\gamma+2(2d+1)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$e_{CJ} = \frac{[(1+d)\gamma+4(2d+1)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Profits	$\pi_{NJ} = q_{NJ}^2 + 2t_{NJ}z_{NJ} - (\gamma/2)z_{NJ}^2$	$\pi_{CJ} = q_{CJ}^2 + 2t_{CJ}z_{CJ} - (\gamma/2)z_{CJ}^2$
Social welfare	$SW_{NJ} = 2Aq_{NJ} - 2q_{NJ}^2 - 2d\{q_{NJ}-2z_{NJ}\}^2 - \gamma z_{NJ}^2$	$SW_{CJ} = 2Aq_{CJ} - 2q_{CJ}^2 - 2d\{q_{CJ}-2z_{CJ}\}^2 - \gamma z_{CJ}^2$

Appendix B

We investigate the mechanism underlying Proposition 3. In the last paragraph of Subsection 4.2, we stated that the result of Proposition 3(iii) is generated by circumstances such that $z_{CJ} < z_N$. Under case CJ, two firms coordinate the R&D effort levels to maximize joint profits: $\Pi(z_i, z_j; \beta_i = 1 = \beta_j) \equiv \pi_i(z_i, z_j; \beta_i = 1) + \pi_j(z_i, z_j; \beta_j = 1)$. Then the first-order condition at the R&D stage is derived as shown below.

$$\frac{\partial \Pi(z_i, z_j; \beta_i = 1 = \beta_j)}{\partial z_i} = \underbrace{\frac{\partial \pi_i(z_i, z_j; \beta_i = 1)}{\partial z_i}}_{\text{(profit enhancing effect)}} + \underbrace{\frac{\partial \pi_j(z_i, z_j; \beta_j = 1)}{\partial z_i}}_{\text{(joint profit maximization effect)}} = 0. \tag{B.1}$$

The partial derivative of $\Pi(z_i, z_j; \beta_i = 1 = \beta_j)$ comprises the profit enhancing effect and the joint profit maximization effect. The first-order condition (B.1) above requires that the summation of two effects is equal to zero.

When $\partial \Pi(z_i, z_j; \beta_i = 1 = \beta_j)/\partial z_i$ is evaluated at $(z_i, z_j) = (z_N, z_N)$, the result is obtained as shown below.

$$\left.\frac{\partial \Pi(z_i, z_j; \beta_i = 1 = \beta_j)}{\partial z_i}\right|_{\substack{z_i = z_N \\ z_j = z_N}} = \underbrace{\left.\frac{\partial \pi_i(z_i, z_j; \beta_i = 1)}{\partial z_i}\right|_{\substack{z_i = z_N \\ z_j = z_N}}}_{=0} + \left.\frac{\partial \pi_j(z_i, z_j; \beta_j = 1)}{\partial z_i}\right|_{\substack{z_i = z_N \\ z_j = z_N}} = \left.\frac{\partial \pi_j(z_i, z_j; \beta_j = 1)}{\partial z_i}\right|_{\substack{z_i = z_N \\ z_j = z_N}} \gtrless 0. \tag{B.2}$$

From (B.2), we understand that $z_{CJ} < z_N$ if the profit-enhancement effect is dominated by the joint maximization effect (if $\gamma < \hat{\gamma}_N$ (see footnote 27)). However, $z_{CJ} > z_N$ if the profit enhancing effect dominates the joint maximization effect.

Appendix C. Supplementary material

Supplementary material to this article can be found online at http://dx.doi.org/10.1016/j.econmod.2016.01.025.

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